GUIDELINES FOR MAPPING SEA LEVEL RISE INUNDATION for WASHINGTON STATE
Purpose

This document provides guidelines for mapping sea level rise inundation throughout Washington State. These guidelines are primarily directed towards staff members with a GIS background who may be asked to prepare maps showing the extent of relative sea level rise inundation.

Although these guidelines could be used to map sea level rise inundation for any available projections the focus is on the new localized projections developed as part of the Washington Coastal Resilience Project. The Washington Coastal Resilience Project is a three-year effort to rapidly increase the state’s capacity to prepare for natural events that threaten the coast. The project will improve risk projections, provide better guidelines for land use planners and strengthen capital investment programs for coastal restoration and infrastructure. The new projections are described in an accompanying technical report, along with a review of the science related to sea level rise (Miller et al., 2018). The report and all associated data are provided on the Washington Coastal Hazards Resilience Network website (http://www.wacoastalnetwork.com/).

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<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>BE</td>
<td>Bare Earth, the version of lidar data appropriate for mapping SLR inundation (same as DTM)</td>
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<tr>
<td>BFE</td>
<td>Base Flood Elevation</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer-Aided Design or Computer-Aided Drafting</td>
</tr>
<tr>
<td>CIG</td>
<td>Climate Impacts Group</td>
</tr>
<tr>
<td>Datum</td>
<td>Any quantity or set of quantities that may serve as a reference or basis for calculating other quantities</td>
</tr>
<tr>
<td>DEM</td>
<td>Digital Elevation Model</td>
</tr>
<tr>
<td>DSM</td>
<td>Digital Surface Model, lidar data including buildings and trees</td>
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<tr>
<td>DTM</td>
<td>Digital Terrain Model, bare earth lidar data</td>
</tr>
<tr>
<td>Ellipsoid</td>
<td>Geometric surface that is an approximation of the earth's surface in size and shape</td>
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<tr>
<td>EPA</td>
<td>Environmental Protection Agency</td>
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<tr>
<td>FEMA</td>
<td>Federal Emergency Management Agency</td>
</tr>
<tr>
<td>FIRM</td>
<td>Flood Insurance Rate Map</td>
</tr>
<tr>
<td>Geoid</td>
<td>An approximation of the shape of the earth. Usually referenced to the height of mean sea level, the geoid provides a consistent basis for defining elevations on the globe. There are different approximations of the Earth's geoid, resulting from different assumptions about the distribution of mass both within the Earth and on its surface.</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographic Information System</td>
</tr>
<tr>
<td>Hillshade</td>
<td>A technique used to visualize terrain as shaded relief, illuminating it with a hypothetical light source.</td>
</tr>
<tr>
<td>Term</td>
<td>Description</td>
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<tr>
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<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
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<tr>
<td>Lidar</td>
<td>Light Detection and Ranging</td>
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<tr>
<td>MHHW</td>
<td>Mean Higher High Water</td>
</tr>
<tr>
<td>NAVD88</td>
<td>North American Vertical Datum of 1988</td>
</tr>
<tr>
<td>NEP</td>
<td>EPA’s National Estuary Program</td>
</tr>
<tr>
<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
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<tr>
<td>PSLC</td>
<td>Puget Sound Lidar Consortium</td>
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<tr>
<td>PSP</td>
<td>Puget Sound Partnership</td>
</tr>
<tr>
<td>RCP</td>
<td>Representative Concentration Pathway: the name for the most recent set of greenhouse gas scenarios (see Section 1 of Mauger et al., 2015)</td>
</tr>
<tr>
<td>Raster</td>
<td>A spatial data model that defines space as a matrix of cells organized in rows and columns. Each cell contains a value representing information, such as elevation.</td>
</tr>
<tr>
<td>RISA</td>
<td>Regional Integrated Sciences and Assessments</td>
</tr>
<tr>
<td>Risk MAP</td>
<td>Risk Mapping, Assessment, and Planning. A FEMA program aimed at supporting communities in their flood risk management. This generally includes the development of new FIRM, but also includes other tools and information related to flood risk management.</td>
</tr>
<tr>
<td>RMSE</td>
<td>Root Mean Squared Error. A measure of the error in a measurement or simulation, calculated by taking the square root of the sum of the individual squared errors.</td>
</tr>
<tr>
<td>RSLR</td>
<td>Relative Sea Level Rise. The relative rise in sea level, compared to an adjacent land area.</td>
</tr>
<tr>
<td>SLR</td>
<td>Sea Level Rise</td>
</tr>
<tr>
<td>SWL</td>
<td>Still Water Level. The water surface elevation, including all factors that can be estimated from tide gauge observations: tides, sea level rise, and surge. SWL does not include the effect of waves.</td>
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<tr>
<td>Acronym</td>
<td>Description</td>
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<tr>
<td>USACE</td>
<td>US Army Corps of Engineers</td>
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<tr>
<td>VLM</td>
<td>Vertical Land Motion</td>
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<tr>
<td>WADNR</td>
<td>Washington Department of Natural Resources</td>
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<td>WSG</td>
<td>Washington Sea Grant</td>
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BASICS OF MAPPING SEA LEVEL RISE

Mapping sea level rise (SLR) inundation requires that you first determine the elevation of your water level (or datum) of interest. SLR projections provide the change in water elevation; to make maps, this change needs to be applied to some baseline water level. In many cases the exposure to daily inundation is of primary interest, leading many users to map how sea level rise will change the daily average high tide (typically this is Mean Higher High Water, or MHHW). In other instances there may be an interest in assessing how sea level rise will impact lower intertidal habitats, in which case a tidal datum associated with lower water levels may be of interest. Or, the focus may be on high water levels during coastal storms, in which case users will want to map an extreme water level datum (e.g., the 10-year coastal flood). In all cases, the process is the same: this datum is used as the base elevation, to which the relative sea level rise (RSLR) projections are added.

\[
\text{Future water level} = \text{datum} + \text{RSLR}
\]

\[
\text{datum} = \begin{cases} 
\text{Low Tide (MLLW)}, \\
\text{High Tide (MHHW)}, \\
\text{10-year surge}, \\
\text{Base Flood Elevation (BFE)}, \\
\text{etc.}
\end{cases}
\]

It is important to carefully consider the choice of datum and interpret the resulting maps accordingly. For example, there is a substantial difference between inundation during a typical high tide (e.g., MHHW) and what is experienced during a storm event (e.g., the 10-year coastal flood). In the first case, high tide inundation is experienced on average once a day, whereas in the second it is a rare event lasting anywhere from a few hours to several days, after which water levels return to normal tidal levels. The impacts associated with these two cases are quite different, as are the adaptations that may be needed to accommodate each. Additionally, flooding associated with extreme coastal storms can result from a variety of processes: a combination of high tidal water level, storm surge and perhaps wave run-up. Different tidal datums may not include the water level influences associated with one or more of these processes, which is important when considering and interpreting sea level maps. For example, a sea level rise map drawn using the 10-year surge as a datum does not include the additional water level influences associated with waves, whereas the FEMA 100-year flood (referred to as the “Base Flood Elevation”, or BFE) does attempt to account for the role of waves in coastal flooding.
These guidelines describe a simplified “bathtub” approach to mapping sea level rise inundation (see **Bathtub Model**, below). This means that we do not consider the dynamics of water motion (“hydrodynamics”) – waves, currents, vegetation and land cover – which can have an effect on the depth and extent of flooding. In the bathtub approach, we simply calculate an estimated water level by summing the influence of various water level components (**Equations 1 and 2**), and then considering anything below that elevation to be underwater. This is an approximation, since some processes that drive coastal flooding – run-up of waves onto the shore, for example – involve hydrodynamic effects that alter the extent and duration of flooding. Hydrodynamic modeling can be used to represent these effects, and the resulting water surface elevation can be represented using a bathtub model. However, bathtub modeling cannot represent the changes in hydrodynamic processes as a result of sea level rise. Although potentially more accurate, hydrodynamic modeling is expensive and hard to implement at a large scale.
How is this different from FEMA mapping?

The future sea level maps described here are different from the coastal flood risk assessments and associated Base Flood Elevation (BFE) used by the Federal Emergency Management Agency (FEMA). Specifically:

1. SLR projections concern future changes in sea level, whereas **FEMA flood maps are based on historical observations and assume no long-term change in risk**.

2. FEMA studies are focused on estimating the total water level elevation, including the influence of waves, associated with one specific event – the 100-year coastal flood – and do not address water levels during normal tides or other storm intensities. In contrast, these guidelines can be used to map potential exposure associated with any tide or storm event of interest.

3. FEMA flood studies include hydrodynamic effects such as currents and wave run-up. In these guidelines we describe a simpler “bathtub” approach, which cannot directly account for hydrodynamic effects on coastal flooding.

FEMA’s RiskMAP program occasionally provides “BFE+ Grids”, which show increases of 1, 2, and 3 feet above the BFE for coastal areas. These are not specifically identified as sea level rise projections, nor are they assigned any particular time period, probability, or scenario. As described in this report, Miller et al. (2018) provide relative sea level rise projections that are specific to particular scenarios, time periods and probabilities. These are provided in increments of 0.1 foot, and range from 0 to more than 6 feet.

The NOAA Office for Coastal Management has produced methods for mapping SLR inundation (**Appendix A: Detailed Method for Mapping Sea Level Rise Inundation, NOAA Office for Coastal Management, 2017**). The document includes detailed steps, using ArcGIS™ software, for generating all of the data needed to map SLR inundation. The methods involve generating a water surface in the same vertical datum as your DEM, adding a sea level rise raster to the water surface, and subtracting your DEM from the water surface to produce an inundation raster. Methods for evaluating connectivity of low-lying inland areas are also included. We have reviewed this approach and consider it to represent best practice for creating SLR inundation maps. However, the NOAA (2017) methodology does not provide information on how to obtain and evaluate
data sources for mapping, nor does it describe any options for addressing errors or artifacts in the data.

Our guidelines, outlined below, are intended to supplement the NOAA (2017) methodology by helping you identify and select the inputs required for mapping: Relative sea level rise (RSLR) projections, local DEMs (Digital Elevation Models), and a baseline water level surface specific to locations in Washington State. In addition, we suggest a different sequence of steps to use in creating the maps and also discuss potential errors in the DEM and tidal datums, along with possible approaches to addressing such errors. Some broader considerations are also discussed, including color choices, CAD drawings, etc.
USING RELATIVE SEA LEVEL RISE PROJECTIONS

Until new science becomes available, we recommend using the new Washington State sea level rise projections (Miller et al., 2018) described below. However, it can be helpful to take a first look at the implications of sea level rise before beginning to create your own maps. As a result, we include instructions on using NOAA’s Sea Level Rise Viewer (https://coast.noaa.gov/slr/) in Appendix B.

New Washington State Sea Level Rise Projections

The new Washington State RSLR projections are described in an accompanying technical report, along with a review of the science related to sea level rise (Miller et al., 2018). As noted above, these data are all provided on the Washington State Coastal Hazards Resilience Network website (http://www.wacoastalnetwork.com/). Because of variations in vertical land motion (VLM), the RSLR projections vary along the coastline of Washington State. Projections are provided as a series of Excel and ArcGIS raster files, both at a resolution of 10 km. The latter are intended for use in mapping.

RSLR projections are provided for each decade from 2010 to 2150 (relative to the average sea level between 1991-2009), for 10 different probabilities of exceedance (99, 95, 90, 83, 50, 17, 10, 5, 1, 0.1%), and for two different greenhouse gas scenarios (Representative Concentration Pathways, or RCPs; see Section 1 of Mauger et al., 2015). VLM estimates are also provided in the same format, so that users can easily incorporate updated SLR projections as new science becomes available. It is important to note that we do not provide a single estimate of the precision in our projections. Instead, the probabilities provide a more complete measure of the range among projections for each time interval and scenario.

In some cases, it may be preferable to evaluate the likelihood of experiencing a certain amount of SLR by some decade in the future (e.g., what is the probability that RSLR will reach 1 foot by 2050?). In addition to the magnitude of rise projected for each probability, each Excel file also includes the probability that RSLR exceeds 0, 0.5, 1, 1.5, 2, 2.5, 3, 4, 5, 6, 7, 8, 9, or 10 feet of rise for each decade through 2150. This information is not included in the ArcGIS raster files.
Selecting a time frame, scenario, and probability

It can be difficult to navigate among the numerous timeframes, scenarios or probabilities of RSLR projections that are available. These choices boil down to the management context and a policy decision about the level of risk that is acceptable. Typically, SLR maps are first made to show a wide range of projections as a starting point for discussion. For a specific project or decision, however, a narrower subset of time frames, scenarios, and probabilities may need to be selected. These selections should be made by the managers or decision-makers responsible for the plan, project, etc. In a companion report (Faghin et al., 2018), we describe a set of steps to take in selecting the appropriate RSLR projections for a specific management situation.

In some cases, there may be a desire to “pick a number”. Although we do not recommend selecting a single projection for use in every decision related to sea level, it may be possible to select a subset of scenarios that could be reasonably applied across a wide range of situations. To identify an appropriate subset, we recommend first going through the steps outlined by Faghin et al. (2018) for a number of specific cases in order to better gauge which choices have the widest applicability.

Incorporating Water Level During Storm Events into SLR Maps

In many situations, the primary management consideration is not the change in high tide but the extent of flooding during storm events. Extreme events could range from the annual average extreme storm to a worst-case event (e.g., 1,000-year flood). As noted in the previous section, elevated coastal water level during storms is a result of both storm surge and waves.

We define storm surge in Washington State as the difference between the measured water level at a particular location and the predicted water elevation due to tides. This difference is the result of two processes: (1) an elevation of the water level in response to a drop in surface pressure, and (2) water movement driven by surface winds. Storm surge is directly measured by tide gauges and therefore relatively easy to estimate. Since several tide gauges have been in place in Washington State for decades, we have long records from which to estimate the likelihood and magnitude of extreme surge events.

By contrast, wave run-up is much more difficult to estimate in coastal Washington, both due to a lack of wave observations and due to the hydrodynamic effects that influence wave set-up and run-up (wave direction, shoreline shape, surface roughness, etc.). Flooding due to waves is also fundamentally different than that due to storm surge:
waves move the surface up and down relative to the storm surge elevation on a time scale of seconds, whereas surge events can last for hours or even days. Because of their short duration and dependence on coastal features, waves are not well represented in bathtub models. Storm surge, in contrast, operates on long enough time scales that bathtub modelling can accurately capture the implications for coastal flooding.

If available, water surface elevations from a hydrodynamic model (e.g., the FEMA Base Flood Elevation, or BFE) can be mapped with a bathtub approach. However, bathtub modeling cannot represent the changes in hydrodynamic processes as a result of sea level rise. Although these can provide a useful first approximation, such results should be interpreted carefully.

Forthcoming work will clarify how storm surge varies across Washington’s coastline, while also providing storm surge anomalies and wave run-up estimates for distinct regions along Washington's coastline (Miller et al. 2019). These can be used to obtain extreme water level estimates for your area of interest. In the interim, storm surge estimates can be obtained from the NOAA Tides and Currents page (http://tidesandcurrents.noaa.gov/) for each tide gauge (see charts entitled “Extreme Water Levels”, under the “Tides/Water Levels” menu for each tide gauge).
SELECTING AND TRANSFORMING ELEVATION DATA

Accurate elevation data is vital for mapping SLR inundation. Lidar data, with its accuracy and fine scale, is well suited for this purpose. FEMA recommends that the vertical accuracy (root mean squared error, or RMSE) for a DEM for mapping inundation is less than 18.5 cm. This level of accuracy is actually quite coarse, and may not be sufficient to map the extent of RSLR for some projections. The RMSE for lidar datasets is generally much lower than this value. Before using lidar data, additional processing is needed to remove artifacts over water bodies ("hydro-flattening") and account for hydraulic connectivity (e.g., a culvert allowing water to cross a road).

Lidar data

Lidars measure the height of the earth's surface by measuring the time it takes for a laser pulse to travel from its observing platform (typically, a plane) to the ground and back. These data include "first returns", which include the tops of buildings and trees as well as the height of the ground surface. For SLR inundation the height of the ground surface is needed: this is referred to as the "bare earth" lidar, in which the buildings and trees have been removed.

Many lidar surveys have been conducted in western Washington. Most are available through either the Washington Department of Natural Resources' Washington Lidar Portal (http://lidarportal.dnr.wa.gov/) or the NOAA'S Office for Coastal Management's Digital Coast Data Access Viewer (https://coast.noaa.gov/dataviewer/#/lidar/search/). Many of these surveys have been conducted under an inter-agency contract managed by the Puget Sound Lidar Consortium (PSLC; http://pugetsoundlidar.org). The surveys in the inter-agency collection have similar technical specifications (e.g., accuracy, geoid). Other lidar surveys in the region, conducted by other agencies, may have different specifications). In general, all lidar surveys use NAVD88 as a vertical datum. However, some may utilize different geoids, which can have the effect of introducing up to an inch of bias into the DEM. If the region for your project has multiple lidar surveys, later surveys generally have higher resolution and accuracy – though this should always be confirmed by consulting the metadata. Most lidar surveys conducted in western Washington are available on all three websites listed above.

The WADNR Lidar Portal is a product of the Washington Geological Survey, which the
FIGURE 1. The Washington Lidar Portal shows the footprints of the lidar surveys conducted in the state that you can download (Source: https://www.dnr.wa.gov/lidar, accessed on 13 September 2018).
state Legislature mandated in 2015 to collect and distribute lidar data. Downloading lidar data via the WADNR or NOAA websites is recommended over the PSLC website for a more consistent experience, as the PSLC website is nearing retirement.

The download pane on the WADNR portal allows for display of hillshades of either a Digital Surface Model (DSM) or a Digital Terrain Model (DTM), and download of both hillshades and data for DSMs and DTMs. DSMs are the “first return” lidar dataset. In the WADNR portal’s terminology, a DTM is equivalent to a DEM, both of which represent the bare earth version of the lidar data. DTMs are the appropriate dataset to use for determining SLR inundation.

**Hydro-Flattening the DEM**

An important step not described in the NOAA (2017) methodology is to “hydro-flatten” the DEM (Figure 2). Processing of raw lidar data into a DEM may result in there being elevation values inappropriately interpolated across water, for instance in narrow channels. A detailed coastline polygon geodataset is used to hydro-flatten a DEM; these datasets can often be obtained from local jurisdictions or counties. Convert the coastline dataset to a raster at the same resolution and cell alignment as the DEM, then use raster algebra to set the value of water pixels in your raster to -99 or NODATA.

![Figure 2](http://www.sanborn.com/hydro-flattening-case-study) Reproduced with permission from the Sanborn Map Company, Inc. © 2018. All rights reserved.
Hydraulic continuity

Some further editing of the DEM data may be required for establishing hydraulic continuity. In particular, dikes and culverts are not always represented correctly in lidar data.

Lidar data will generally not show the correct elevation of dikes and levees. While some lidar “hits” may be on the top of a dike, processing of lidar data by the vendor will average these points with points on either side of the dike, such that the elevation of the dike is too low in the DEM. This could result in low-lying areas behind the dike incorrectly being portrayed as inundated at a water level that is actually below the dike. Many jurisdictions have surveyed these features and can provide accurate elevations that should be used to correct the DEM. If no survey is available, the highest elevation of the dike in the DEM could be extended to the entire dike. Alternatively, you could examine the original point cloud data from the lidar, if available, to determine the height of the dike or levee.

The DEM may show the elevation of a structure (e.g., bridge, pier, elevated roadway) rather than the surface under that structure, in which case the DEM should be corrected to ‘remove’ the bridge. In addition, a DEM will not represent hydraulic connections through a culvert or other stormwater infrastructure. Many jurisdictions have geospatial information on such infrastructure. Having accurate elevation data for this infrastructure helps to identify low-lying areas that are hydraulically connected with ocean and estuarine water levels.

You may be able to do this preemptively, or it might be easier to do so iteratively. If hydraulic continuity can be established and edited into the DEM before adding RSLR values to your DEM, inundation of low-lying inland areas will be correctly mapped immediately. Alternatively, hydraulic continuity can also be determined after disconnected low-lying areas are identified (steps 4-6 in NOAA, 2017). In this way, checking and correcting for hydraulic continuity can be done iteratively. Since you will likely be mapping several different SLR scenarios, the first approach – representing the elevations of dikes, levees, culverts, and stormwater infrastructure correctly in the DEM – may be more efficient than iterating for each scenario you wish to map. If you do not have the elevation data for this infrastructure, iterating for each scenario will be necessary.
Vertical Datum Transformation

When mapping SLR inundation, it is essential that both the land elevation and water level datasets be in the same vertical datum. Lidar data will almost always be in NAVD88, though DEMs from some providers may be registered to another datum (e.g. NOAA DEMs give the elevation relative to Mean Higher High Water (MHHW)). Impacts associated with SLR are typically assessed for a high tidal datum, such as MHHW, in order to evaluate the maximum extent of inundation on an average day. However, MHHW is a tidal datum, and needs be transformed to NAVD88 to map SLR inundation. NOAA's Office for Coastal Management offers a MHHW water surface that is vertically referenced in NAVD88. This dataset can be downloaded from the NOAA Data Catalog (https://data.noaa.gov/dataset/dataset/inundation-mapping-tidal-surface-mean-higher-high-water).

Alternatively, you can also create your own MHHW surface using NOAA's VDatum software (https://vdatum.noaa.gov/). Instructions for doing this are included in the NOAA (2017) methodology in Appendix A. There is a key advantage to using the surface that NOAA provides instead of using VDatum, which is that it maps inland areas that may become inundated. The data underlying VDatum does not extend inland past the shoreline, and so does not provide coverage for such areas. If you prepare your own MHHW surface, you must extend it inland in order to map these areas correctly. NOAA's MHHW surface uses a rigorous method to interpolate the data inland, as described in its metadata. To save time and to take advantage of NOAA's more rigorous interpolation, we recommend that you use the MHHW surface provided by NOAA whenever possible.

The following is the abstract from the NOAA (2017) metadata:

“These data are a derived product of the NOAA VDatum tool and they extend the tool’s Mean Higher High Water (MHHW) tidal datum conversion inland beyond its original extent.

VDatum was designed to vertically transform geospatial data among a variety of tidal, orthometric and ellipsoidal vertical datums - allowing users to convert their data from different horizontal/vertical references into a common system and enabling the fusion of diverse geospatial data in desired reference levels (http://vdatum.noaa.gov/). However, VDatum’s conversion extent does not completely cover tidally-influenced areas along the coast. For more information on why VDatum does not provide tidal datums inland, see http://vdatum.noaa.gov/docs/faqs.html."
Because of the extent limitation and since most inundation mapping activities use a tidal datum as the reference zero (e.g., 1 meter of sea level rise on top of Mean Higher High Water), the NOAA Office for Coastal Management created this dataset for the purpose of extending the MHHW tidal datum beyond the areas covered by VDatum. The data do not replace VDatum, nor do they supersede the valid datum transformations VDatum provides. However, the data are based on VDatum’s underlying transformation data and do provide an approximation of MHHW where VDatum does not provide one. In addition, the data are in a GIS-friendly format and represent MHHW in NAVD88, which is the vertical datum by which most topographic data are referenced.

Data are in the UTM NAD83 projection. Horizontal resolution varies by VDatum region, but is either 50m or 100m. Data are vertically referenced to NAVD88 meters.

VDatum is updated regularly. The NOAA MHHW dataset is also updated whenever VDatum is updated, and the latest version of each should always be used. The raster resolution of the MHHW dataset over Washington State is 100m.

A limitation of the VDatum dataset is that it is based on NOAA’s tide gauges, and areas that are far from a tide gauge may not be accurately represented. Similarly, errors stemming from a faulty tide gauge could result in a biased transformation for nearby coastal areas. As a result, some local applications will require surveys or the placement of a temporary tide gauge to determine the correct datum transformation in VDatum and a better MHHW surface. An example from Tacoma is included in Appendix B of this document.

For more information about the geoid, ellipsoids, orthometric datums and tidal datums, and how they relate to each other, see NOAA’s webpage “A Tutorial on Datums” (https://vdatum.noaa.gov/docs/datums.html).
CREATING SEA LEVEL RISE MAPS

Map Symbolization

There are several different dimensions and attributes of RSLR data. Inundation maps can be made with gradients of any of them. Dimensions include time, likelihood, and greenhouse gas scenario. Forthcoming datasets from the WCRP project will include storm surge; another dimension that can be displayed.

Since the attributes of SLR are ordered numerical data, they should be symbolized using a sequential color scheme (i.e., one that uses light to dark colors to represent “less” to “more”). ColorBrewer2 (http://colorbrewer2.org, Figure 3) is a very useful tool to choose color schemes. It includes both multi-hue and single-hue sequential color schemes, but the primary variation is in lightness, not hue. Many of the color schemes in ColorBrewer2 include blue hues, intuitively appropriate for mapping water.

In our experience, it is helpful to include the current MHHW level as a reference, as the darkest shade. Light to dark colors should correspond to lower to higher likelihood of SLR, respectively.

![Figure 3. Screenshot from ColorBrewer2.org](http://colorbrewer2.org)
Mapping Multiple Likelihoods

Since SLR is provided in probabilities – there is no single correct “answer” for what the future will hold – often the best approach is to map a range of SLR projections. While we provide 10 different likelihoods for each decade, this may be too many categories to be readable on a single map. The usual recommendation for the maximum number of categories to show on a map is five to seven, but given that the areas inundated by

![Kilisut Harbor Map](image)

**FIGURE 4.** Example SLR inundation map, showing the multiple probabilities of future RSLR inundation for Kilisut Harbor, at the south end of Marrowstone and Indian Islands in Puget Sound. The map shows the area inundated by future high tide (MHHW) due to SLR. Projections include a range of probabilities for sea level in 2150 relative to 2000, for a high greenhouse gas scenario (RCP 8.5; Miller et al., 2018).
different likelihoods of SLR are often small and narrow, we recommend displaying no more than four categories. Recent SLR maps produced by Washington Sea Grant, for example, used four likelihoods (50%, 25%, 5%, and 1%) and only mapped the upper half of the probability distribution (Petersen et al., 2015). Other reasonable combinations of categories are 17%, 50%, and 83% (50% ± 33%, or the central 66% of the distribution); 10%, 50% and 90%; 5%, 50%, and 95%; and 1%, 50%, and 99%. An example figure is shown in Figure 4.
Mapping Multiple Future Time Periods

Alternatively, maps showing the same likelihood for a sequence of time periods may be useful. As an example, Figure 5 shows which areas are projected to have a 50% chance of being inundated in 40-year increments. Again, a sequential color scheme is appropriate. In this case, dark to light colors should represent the soonest to latest time periods, respectively.

FIGURE 5. As in Figure 4, except showing the central estimate (50% probability) projection for four different time periods: 2030, 2070, 2110, and 2150; all relative to 2000 (1991-2009; data from Miller et al., 2018).
Mapping Inundation Depth

You may also wish to map inundation depth for a given level of RSLR (Figure 6). Once again, a sequential color scheme is appropriate. In this case, light to dark colors should represent the shallowest to deepest inundation, respectively.

**FIGURE 6.** As in Figure 4, except showing the depth of inundation for the median (50% probability) projection for 2150. Depths are only shown for areas beyond the current high tide extent (MHHW in 2000). Data from Miller et al. (2018).
Determining if Inland Low-Lying Areas Will Flood

Often there are low elevation areas that are separated from the water by a berm or other obstruction (Figure 7). As noted above, it is important to identify those that are hydraulically connected and map them accordingly. In addition, some inland areas may flood in the future whereas they did not in the past. You may wish to symbolize these areas with a unique color and explanation in the legend.

**FIGURE 7.** As in Figure 4, except showing RSLR inundation for Dockton, on Maury Island. The map is based on two projections for 2120: the 5% probability for RCP 4.5, and the 1% probability for RCP 8.5. Inundation is projected for an inland low-lying area, which can be seen just to the left and above the map legend (Miller et al., 2018).
Storm Surge Inundation

Although storm surge can be mapped using the same techniques as for sea level rise, a surge event is very different than a change in the elevation of high tide (Figure 8). This means it is important for the map to highlight the distinction between flooding that would be experienced on a daily basis, and, for example, the area flooded during a 10-year surge event.

**FIGURE 8.** As in Figure 4, except showing the depth of inundation for the median (50% probability) projection for 2100 during high tide (MHHW) as well as due to a 100-year storm surge event. Projections are shown relative to high tide (MHHW) in 2000. Data from Miller et al. (2018).
ADDITIONAL CONSIDERATIONS

Raster Processing

When using multiple raster geodatasets in GIS processing, it is important to be aware of how your software combines rasters of differing cell resolutions, cell alignments and projections. You should use your DEM as the basis for cell resolution, cell alignment and projection. You can control how other rasters work with your DEM using settings, or by explicitly reprojecting or resampling those rasters to the same resolution, alignment or projection as your DEM.

ArcGIS Environment Settings

There are several environment settings that are important to set when working with raster data in ArcGIS. In particular, it is always good practice to use the Processing Extent: Snap Raster environment setting when using any raster geoprocessing tool. This setting should be set to your DEM, to ensure that the cell alignment does not vary from your DEM.

The datasets you will use in mapping SLR inundation come in several cell sizes (DEM: 1-5 m, RSLR: 100 m, NOAA MHHW: 100 m). When combining rasters of different resolutions, ArcGIS will default to providing output at the coarsest resolution of the input rasters. To override this, set the Raster Analysis: Cell Size setting to your DEM.

You may also find the Raster Analysis: Mask and the Processing Extent: Extent settings useful for some steps in your analysis.

Errors in MHHW

Previous studies by the University of Washington Climate Impacts Group and Washington Sea Grant have identified an error in how NOAA’s VDatum calculates MHHW along the outer coast, in particular on the central coast of Washington near the Toke Point tide gauge (NOAA ID: 9440910). Other errors may exist elsewhere, particularly in locations not near a tide gauge. If you suspect errors in MHHW, you may wish to set up your own tidal gauge for a period of time and use its data as an input to VDatum, or in lieu of VDatum, as mentioned in section 5 above.
CAD

For site-specific project planning, you may be using computer-aided design (CAD) software rather than GIS (Figure 9). Generally speaking, the approach to mapping SLR in CAD software is similar to the approach outlined for GIS. It is important to be aware of the vertical datum that the elevations and contours in the CAD data are referenced to (often NGVD29), and to make the appropriate conversion to MHHW. The previous section entitled “Vertical Datum Transformation” (page 20) describes approaches for translating among vertical datums. In addition, the diagram in Appendix C is helpful for visualizing datum conversions.

Figure 9. Example CAD drawing showing sea level rise elevations. Source: Ryan Storkman (www.siteworkshop.net) and Metro Parks Tacoma (2018). Reproduced with permission.
Vertical Land Motion limitations

Fine scale variations in land surface elevation due to factors such as sediment compaction and groundwater extraction are not captured well by our VLM model due to the relative coarseness of the measurement stations and the emphasis on providing stable reference sites. If you suspect local rates of VLM differ from those assessed by Miller et al. (2018), you may want to obtain independent estimates for your area of interest. Options include identifying additional benchmark surveys and evaluating results from Interferometric Synthetic Aperture Radar (InSAR).

Bathtub Model

The mapping method described in NOAA’s 2017 guidance (Appendix A) is a “bathtub” approach. That is, SLR is statically added to current sea level and the results are similar to what you would see in a bathtub. However, the dynamics of water motion (or hydrodynamics) can either lead to greater or lesser impacts depending on the circumstance. For example, wave setup and run-up can lead to greater inundation in some areas, while flow constrictions or friction can limit the extent of inundation during high tide. Other factors include shoreline erosion, ocean currents, and river flows. Hydrodynamic effects also vary spatially (e.g., the outer coast is more dynamic than protected bays). More sophisticated modeling is required to capture these effects. The bathtub modeling approach described here is intended to provide an inexpensive first approximation of future sea level rise inundation.

Temporal Incompatibility

The MHHW data underlying VDatum is based on the National Tidal Datum Epoch (NTDE), a 19-year period. The current epoch, 1983-2001, was adopted in 2003. NOAA’s National Ocean Service considers a revision of the NTDE every 20 to 25 years, to account for SLR and VLM.

NOAA DEM

NOAA’s Sea Level Rise Viewer (https://coast.noaa.gov/slr/) includes a DEM for Washington State. This DEM uses lidar data from PSLC and other sources from 2012 and before. NOAA intends to update the DEM in 2018 or 2019 with new lidar data from PSLC and other sources. NOAA also resamples the DEM to a coarser resolution (5 m) than the original lidar. As a result, we do not recommend using NOAA’s current SLR DEM if there is lidar in your project area that is more recent than 2012, or if you require a finer
resolution than is provided by NOAA. As noted above, original lidar datasets can be obtained from multiple sources, such as the Washington Lidar Portal (http://lidarportal.dnr.wa.gov/).
OTHER FLOOD AND SLR MAPPING

FEMA RiskMap program

FEMA’s RiskMAP program is in the process of updating Flood Insurance Rate Maps (FIRMs) for Washington’s coastline. RiskMap uses Base Flood Elevation (BFE) as a basis for flood insurance and flood risk management. BFE is the 1% annual chance flood, or 100-year event, based on historical data. It includes the hydrodynamic effects of wave set-up and run-up, and is typically referenced to a geodetic instead of a tidal datum.

In their Risk Reports, FEMA occasionally provides “BFE+ Grids”, which they typically define as follows:

“The Base Flood Elevation (BFE)+ grid shows increases of 1, 2, and 3 feet above the BFE for the coastal areas. This grid can be used to represent flood events that exceed the 1-percent-annual-chance flood. The BFE+ grid can be used to identify areas affected by increased storm surge, storms greater than the 1-percent-annual-chance event, and areas potentially affected by sea level rise.” (Source: Michael Levkowitz, personal communication).

As noted previously (see Box entitled “How is this different from FEMA mapping?” on page 11), these elevations are not associated with a particular greenhouse gas scenario. In addition, FEMA is not providing guidance on when, or how likely, these might be. Nonetheless, users can use our RSLR projections to identify the probability associated with 1, 2, and 3 feet of relative sea level rise for different future time periods, then use the BFE+ maps to view the extent and depth of future 100-year floods. In addition, our results can be used to evaluate a complementary set of inundation scenarios such as everyday high tide (MHHW) or other frequencies of extreme events (e.g., the 10% annual chance – or 10-year – surge event).

U.S. Army Corps Sea Level Rise and Vertical Datum Guidance

The U.S. Army Corps of Engineers (USACE) requires that projects under its authority “be reliably and accurately referenced to a consistent nationwide framework, or vertical datum” (e.g., NAVD88). Existing projects referenced to older, superseded datums must accurately document and update the relationship between the older datum and NAVD88 (USACE, 2009). USACE provides extensive technical guidance on how to do this (USACE 2010).
Similarly, USACE provides “guidance for incorporating the direct and indirect physical effects of projected future sea level change across the project life cycle” for USACE projects (USACE, 2013). The USACE (2014) guidance recognizes the significance of relative sea level change, and stipulates that, “Potential relative sea level change must be considered in every USACE coastal activity as far inland as the extent of estimated tidal influence.” Further guidance is provided in USACE (2014).
REFERENCES


APPENDIX A: NOAA METHODOLOGY FOR MAPPING SEA LEVEL RISE INUNDATION
METHOD DESCRIPTION

Detailed Method for Mapping
Sea Level Rise Inundation

January 2017

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Introduction
This document describes the mapping process used by the NOAA Office for Coastal Management to map sea level rise inundation for the Sea Level Rise Viewer. Generally, this process can be described as a modified bathtub approach that attempts to account for local and regional tidal variability and hydrological connectivity.

Goals of Mapping
- Use best publically available and accessible elevation data
- Map literature-supported levels of sea level rise
- Map sea level rise on top of mean higher high water (MHHW)
- Incorporate local and regional tidal variation of MHHW for each area
- Evaluate inundation for hydrological connectivity
- Preserve hydrologically unconnected areas greater than one acre in size, but display separately from hydrologically connected inundation

Caveats and Assumptions
- These data are for planning, educational, and awareness purposes only and should not be used for site-specific analysis, navigation, or permitting.
- The mapping does not incorporate future changes in coastal geomorphology and assumes present conditions will persist, which will not be the case.
- The digital elevation model used to map sea level rise does not incorporate a detailed pipe network analysis, or engineering grade hydrologic analysis (for example, culverts and ditches may not be incorporated resulting in incorrectly mapped areas). Therefore, hydrologically unconnected areas of inundation are still displayed, though symbolized differently than hydrologically connected inundation.
Tidal Surface Creation

To incorporate tidal variability within an area when mapping sea level rise, a “modeled” surface (or raster) is needed that represents this variability. In addition, this surface must be represented in the same vertical datum as the elevation data, which is typically the orthometric datum of NAVD88 (North American Vertical Datum of 1988). Once created, this surface can be used as a current conditions surface upon which sea level rise can be added.

Currently, there are two primary ways this surface can be created. The first and simpler approach is to interpolate a surface using tide gauges and their associated vertical datum conversions. The second and more accurate approach is to use NOAA’s vertical datum conversion software, VDatum (http://vdatum.noaa.gov), which was used by the NOAA Office for Coastal Management. Each process is described below.

Tide Gage Approach

- Use http://tidesandcurrents.noaa.gov to determine which tide gauges are available within the area.
- Select tide gauges where the tidal-to-orthometric-datum relationship or conversion has been calculated.
- Create a point shapefile of the selected tide gauges using their latitude and longitude information and the datum conversion factor/number.
- Interpolate a raster (inverse distance weighted, or IDW; natural neighbor) for the area using the point shapefile.

Considerations

- Include enough tide gauges so that the interpolated surface covers the area of interest.
- Use a raster resolution that will capture the tidal variability for the area: 500 meters (m) or more, up to 3 kilometers (km).

VDatum Approach

- Create a grid of points; this can be generated in a number of ways including converting raster cells to points [Raster to Point]. Point spacing should be on the order of 500 m (1500 feet); smaller grids will increase the size of the file but add very little real improvement. Points should be set to have an elevation of zero.
- Use VDatum* to convert the gridded points to the chosen tidal datum (MHHW). VDatum will only assign values to the points within its model extents; this means inland points will not typically have a real elevation number and will be assigned a -9999 value. Defining the elevation of the inland points is an extra step covered under “Extension of VDatum Water Surface Inland” below.
- Process parameters and steps within VDatum
  1. Select area of interest from drop-down menu in VDatum.
  2. Define Datum Information parameters:
     - Input Vertical Datum: Desired Tidal Datum (MHHW)
     - Output Vertical Datum: Datum of Digital Elevation Model (NAVD88)
3. Input File: X,Y,Z data reflecting points with elevation set to zero.
4. Output file: X,Y,Z data will reflect points with elevations representing the offset between datums.
   - Create a triangulated irregular network (TIN) or interpolated surface (IDW, natural neighbor) from the output points. This is the MHHW water surface in NAVD88 values.
   - In most cases, the VDatum water surface will stop near the shoreline; if the area of analysis extends significantly far inland (e.g., Florida Everglades), then the water surface will need to be extended inland.

*For a detailed guide to using VDatum, visit [https://vdatum.noaa.gov/docs/userguide.html](https://vdatum.noaa.gov/docs/userguide.html).

**Extension of VDatum Water Surface Inland**
- Transect Method – create cross-shore (perpendicular to shoreline) transects that extend inland just past the area of analysis. Transect spacing and locations are at the discretion of the user but should capture the variation in tidal surface; more complex tidal areas will require more transects than simple tidal regimes. Using the water surface elevations along the transect, extend the general tidal trends inland and assign values (substitute transect values for -9999 values) to the grid points nearest the transect’s path – here again, the number of points along the transect are at the discretion of the user and may depend on local variations in the tidal surface elevations. Generate a new surface from the combined VDatum (original values) and transect-generated points.
- Interpolation Method – in some cases an interpolated surface can be used instead of the transect method. These cases include areas where valid VDatum points exist on several sides of the area of interest (i.e., not a straight stretch of shoreline). For these areas, a natural neighbor algorithm is a good place to start. This will generate a fairly smooth surface. To create a more generalized surface, a 1st or 2nd order trend surface can be calculated.

**Considerations**
- Make the initial raster large enough to cover the area of interest.
- Use a raster resolution that will capture the tidal variability for the area: 500 m or more, up to 3 km.

**Detailed Mapping Process**
This process is based on and describes tools and inputs in ESRI’s ArcGIS software. Specifically, this process is intended for ArcGIS 10.3.1 and requires the Spatial Analyst extension.

**Inputs**
- Digital elevation model (DEM)
- Tidal surface in NAVD88 values
- Sea level rise values
Method: Mapping Sea Level Rise Inundation

Process

1. Add desired sea level rise (SLR) amount to tidal surface grid.
   Spatial Analyst > Math > Plus
   - Input raster or constant value 1 = tidal surface
   - Input raster or constant value 2 = SLR amount
   - Output raster = surface_x (where “x” is the SLR amount)

2. Subtract DEM values from water surface to derive initial inundation depth grid.
   Spatial Analyst > Single Output Map Algebra
   - Map Algebra expression: con (DEM <= surface_x, surface_x - DEM)
   - Output raster = depth_x

3. In preparation for evaluating connectivity, create single value DEM to show inundation extent.
   Spatial Analyst > Single Output Map Algebra
   - Map Algebra expression: con (DEM <= surface_x, 1)
   - Output raster = single_x

4. Evaluate connectivity of extent raster.
   Spatial Analyst > Generalization > Region Group
   - Input raster = single_x
   - Number of neighbors to use = 8
   - Zone grouping method = Within
   - Output raster = clumped_x

5. Extract connected inundation surface to be used as a mask for the original depth grid.
   Spatial Analyst > Extraction > Extract by Attributes
   - Input raster = clumped_x
   - Where clause: “Count” = maximum value
   - Output raster = connect_x

6. Derive low-lying areas greater than an acre.
   Spatial Analyst > Extraction > Extract by Attributes
   - Input raster = clumped_x
   - Where clause: “Count” > 40
   - Output raster = lowlying_x

7. Create depth grid for connected areas.
   Spatial Analyst > Extraction > Extract by Mask
   - Input raster = depth_x
   - Input raster or feature mask data = connect_x
   - Output raster = con_depth_x

Optional visualization method to show only impact on land.

1. Spatial Analyst > Reclass > Reclassify
   - Input raster = connect_0
   - Reclass field = Value
   - Value becomes NoData
   - NoData becomes 1
   - Output raster = mask
2. Spatial Analyst > Extraction > Extract by Mask  
   o Input Raster = con_depth_x  
   o Input raster or feature mask data = mask  
   o Output raster = extract_x

**Notes:**

1 Maximum Value is obtained by clicking **Get Unique Values** within the SQL Query Builder; this value represents connected inundation from the open ocean. Some instances may require the user to select more than one Maximum Value depending on the data.

2 The value of 40 is based on the use of 10 m grid cells; 1 acre = 4046.85m², 4046.85 m²/100 m² = 40.46; this value may change depending on the resolution of the DEM.

3 This process must first be executed using data reflecting “current” conditions (i.e. SLR = 0); the mask based upon the “0 SLR” is then used to obtain raster reflecting different levels of sea level rise.
APPENDIX B: HOW TO USE THE NOAA SEA LEVEL RISE VIEWER

Online sea level rise viewers can serve as a useful first step for evaluating sea level rise vulnerability. The NOAA Sea Level Rise Viewer (https://coast.noaa.gov/slr/) allows users to easily map projected sea level rise in one foot increments ranging from zero to six feet. Users can choose the location closest to their area of interest, select a decade (based on the established planning horizon) and view a map of inundation for different amounts of sea level rise.

Although the focus of the NOAA tool is on mapping sea level rise inundation, the tool also relates water elevations to the NOAA SLR projections. It is important to note that these are different than the Miller et al. (2018) sea level projections for Washington State. Although based on the same science, the NOAA projections are (a) based on scenarios instead of probabilities, and (b) do not include a detailed analysis of the effects of vertical land motion. For these reasons, we recommend using the new Washington State SLR projections in lieu of those provided by NOAA.

The following steps, adapted from Peterson et al. (2015), describe how to use the NOAA Sea Level Rise Viewer:

1. Navigate to www.coast.noaa.gov/slr and click “Get Started”
2. Use the +/- buttons to zoom to the area of interest.
3. Select the “Local Scenarios” icon and double click the blue “local scenario” symbol closest to your area of interest.
4. A light blue pop up box will appear on the left side of your screen.
5. Use the slider bar on the right side of the pop up box to choose a planning scenario that you want to visualize (Intermediate-Low, Intermediate, Intermediate High, High or Extreme).
6. Use the slider bar labeled “Water Levels” on the left side of the pop up box and toggle using the “MHHW” button to view the SLR projections (in feet) at a given site (from 1-6 feet.). All maps show the inundation extent at high tide – specifically, MHHW – storm surge and waves are not explicitly included in the tool. Although the tool is geared towards mapping SLR inundation, flooding during storm events can still be evaluated by simply considering a water level corresponding to the sum of the SLR, surge, and wave elevations of interest (Equations 1 and 2).
7. Just to the right of the water levels, SLR projections across year intervals 2020-2100 are provided and allow you to get an idea of approximate sea level rise over time. As noted above, these are based on the NOAA SLR projections, and are different from those described in this report.

8. SLR maps can only be visualized in whole feet. As described below, these can be related to the new Miller et al. (2018) projections by evaluating the probability that sea level rise exceeds a particular threshold.

Shapefiles can also be downloaded, which delineate the extent of flooding associated with sea level rise magnitudes of 0.5, 1, 2, 3, 4, 5 and 6 feet. These could also be used to get a first look at the implications of SLR for your area of interest.